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Review on solar-driven ejector refrigeration technologies

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ABSTRACT

The objective of this paper is to provide a literature review on solar-driven ejector refrigeration systems and to give useful guidelines regarding background and operating principles of ejector. The development history and recent progress in solar-driven ejector refrigeration systems are reported and categorized. It shows that solar-driven ejector refrigeration technologies are not only can serve the needs for cooling requirements such as air-conditioning and ice-making and medical or food preservation in remote areas, but also can meet demand for energy conservation and environment protection. For these reasons, the research activities in this sector are still increasing to solve the crucial points that make these systems not yet ready to compete with the well-known vapour compression system. However, a lot of research work still needs to be done for large-scale applications in industry and for the replacement of conventional refrigeration machines.

Contents

1. Introduction

Refrigeration is available in the industrialised countries through the availability of electricity but is not readily available in the major part of the world. An alternative solution for this problem is solar energy, available in most areas and it represents a good source of thermal energy; the combination of solar energy with absorption, adsorption, desiccant, and others technologies less studied for refrigeration are being investigated and improved around the world.

The production of cold has applications in a considerable number of fields of human life, for example the food processing field, the air-conditioning sector, and the conservation of pharmaceutical products, etc. The conventional refrigeration cycles driven by traditional vapour compression in general contribute significantly

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in an opposite way to the concept of sustainable development. Two major problems have yet to be addressed:

- The global increasing consumption of limited primary energy: the traditional refrigeration cycles are driven by electricity or heat, which strongly increases the consumption of electricity and fossil energy. The International Institute of Refrigeration in Paris (IIF/IIR) has estimated that approximately 15% of all the electricity produced in the whole world is employed for refrigeration and air-conditioning processes of various kinds, and the energy consumption for air-conditioning systems has recently been estimated to 45% of the whole households and commercial buildings [1,2]. Moreover, peak electricity demand during summer is being re-enforced by the propagation of air-conditioning appliances.
- The refrigerants used cause serious environmental problems: the traditional commercial, non-natural working fluids, like the chlorofluorocarbures (CFCs), the hydrochlorofluorocarbures (HCFCs) and the hydrofluorocarbures (HFCs) result in both ozone depletion and/or global warming. It is well known that the stratospheric ozone layer acts as a shield against harmful ultraviolet solar radiation. During the past decade, researchers have discovered that chlorine released from synthetic CFCs migrates to the stratosphere and destroys ozone molecules causing health hazards [3]. Since the protocol of Montreal in 1987, international agreements have been signed to reduce the emissions of these refrigerants [4]. European Commission Regulation 2037/2000, which has been implemented on 1 October 2000, treats the whole spectrum of control and phase-out schedule of all the ozone-depleting substances. It is indicated that till 2015 all HCFCs will be banned for servicing and maintaining existing systems [5].

With developing technology and the rapid increase in world population, the demand for energy is ever increasing. The growing population and fast depleting reserves of fossil fuels have led scientists in the fields of engineering, meteorology and industry to pursue the development and use of renewable energy resources. In the few past decades, researchers have focused on renewable energy sources, such as solar and wind energies. With the use of solar energy, usage of conventional energy sources and its peak demand will be reduced.

Accurate detailed long-term knowledge of the available global solar radiation is of a prime importance for the design and development of solar energy-conversion systems such as ejector refrigeration systems. The possible use of solar energy as the main heat input for a cooling system has led to several studies of available ejector refrigeration technologies.

The ejector is a key component of the ejector refrigeration system. It should be noted that the ejector could increase the pressure without consuming mechanical energy directly, which are the main characteristics of ejectors. Due to these characteristics, applying an ejector may be simpler and safer technologically than applying mechanical devices, which can increase pressure, such as a compressor, pump, etc. Besides the very simple configuration ejectors, the systems combining ejectors and other devices are also very simple.

In the past we have presented reviews on solar adsorption refrigeration, thermal collectors and their materials, Alghoul et al. [6–8] in the hope that this information will be useful to interested readers. We would like now to present a review on solar-driven ejector refrigeration technologies which have potential to be used in many parts of the world. A number of solar-driven ejector refrigeration systems and research options are provided and discussed. These concepts and interesting points of each study were linked and grouped to other related studies and described as overview summaries. It is hoped that this paper should be useful for any newcomer in this field of refrigeration technology.

2. Solar cooling paths

The solar cooling system is generally comprised of three subsystems: the solar energy conversion system, refrigeration system, and the cooling load. The appropriate cycle in each application depends on cooling demand, power, and the temperature levels of the refrigerated object, as well as the environment. A number of possible "paths" from solar energy to "cooling services" are shown in Fig. 1.

Starting from the inflow of solar energy there are obviously two significant paths to follow; solar thermal collectors to heat or PV

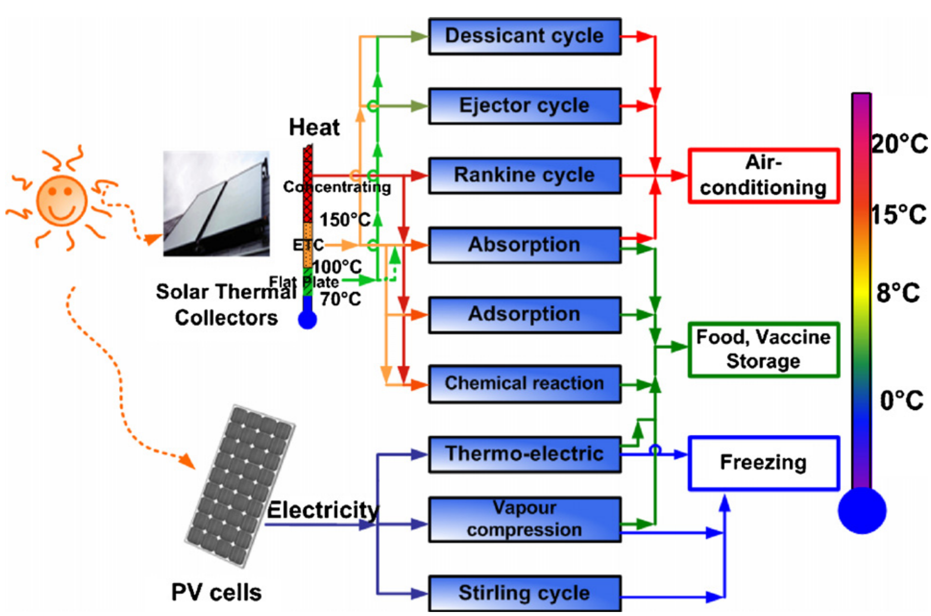

Fig. 1. Solar cooling paths.

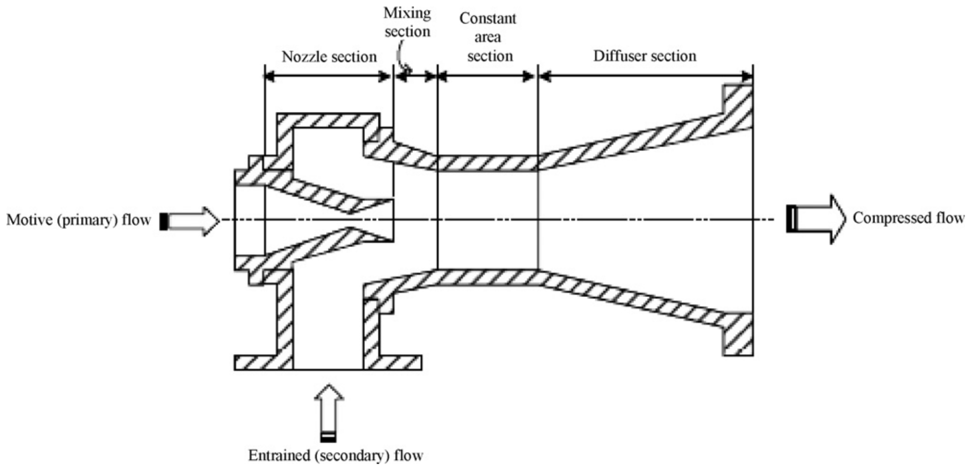

Fig. 2. Schematic diagram of ejector.

cells to electricity. For solar thermal collectors, different collector types produce different temperature levels. This indicates that the temperature level can be matched to various cycle demands. For example, the Rankine cycle (duplex type) requires a rather high driving temperature whereas the desiccant cycle manages at a lower temperature level of heat supply.

The same type of temperature matching is important for the cold side of the solar cooling path, i.e. in the cold object. Since several cycles typically operate with water as a working fluid, it is impossible to achieve temperatures below 0 °C for some cycles. The solar thermal-driven air-conditioning cycles can be based on absorption cycles, adsorption cycles, duplex rankine, desiccant cooling cycles, or ejector refrigeration cycles.

When using low temperature applications for food storage at 0 to −10 °C, various cycles can be applied, i.e. the vapour compression cycle, thermoelectric cycle (Peltier), NH_3–H_2O absorption cycle, adsorption cycle with ammonia as a working fluid or a chemical reaction cycle. Applications requiring temperatures below 0 °C generally require small storage volumes, e.g., freezing boxes. A suitable cycle for this application has proved to be the PV-driven vapour compression cycle, or a PV-driven Stirling cycle. The double effect absorption cycle, adsorption cycle and chemical reaction cycle can also be used, especially for larger storage volumes, i.e. ice production.

3. Background and operation principles of ejector

The ejector, which is the heart of the jet refrigeration system, was invented by Sir Charles Parsons around 1901 for removing air from a steam engine's condenser. In 1910, an ejector was used by Maurice Leblanc in the first steam jet refrigeration system [9]. This system experienced a wave of popularity during the early 1930s for air conditioning large buildings [10]. The ejectors are an essential part in refrigeration and air conditioning, desalination, petroleum refining and chemical industries. Also, the ejectors form an integral part of distillation columns, condensers and other heat exchange processes.

Although the construction and operation principles of jet ejectors are well known, the following sections provide a brief summary of the major features of ejectors. This is necessary in order to follow the discussion and analysis that follow. The ejector mainly consists of a nozzle, a mixing chamber and a diffuser as shown in Fig. 2. The ejector is characterized by the fact that there are no moving parts and no requirement for additional energy source.

The nozzle and the diffuser have the geometry of converging/diverging venturi. The diameters and lengths of various parts forming the nozzle, the diffuser and the mixing chamber, together with the stream flow rate and properties, define the ejector capacity and performance. The ejector capacity is defined in terms of the flow rates of the motive (primary) flow and the entrained (secondary) flow. The sum of the motive and entrained mass flow rates gives the mass flow rate of the compressed flow. There are several parameters used to describe the performance of an ejector. For refrigeration applications, the most important parameters are defined in terms of entrainment, expansion and compression ratios. The entrainment ratio (w) is the flow rate of the entrained flow divided by the flow rate of the motive flow. As for the expansion ratio (Er), it is defined as the ratio of the motive flow pressure to the entrained flow pressure. The compression ratio (Cr) gives the pressure ratio of the compressed flow to the entrained flow.

The entrainment ratio is related to the energy efficiency of a refrigeration cycle and the pressure ratio limits the temperature at which the heat can be rejected [11]. Therefore, there is no doubt that an ejector operating at the given operating conditions with the highest entrainment ratio and maintaining the highest possible discharged pressure will be the most desired ejector.

Variations in stream pressure and velocity as a function of location inside the ejector, which are shown in Fig. 3, are explained below:

- The motive flow enters the ejector at point (p) with a subsonic velocity.
- As the stream flows in the converging part of the ejector, its pressure is reduced and its velocity increases. The stream reaches sonic velocity at the nozzle throat, where its Mach number is equal to one.
- The increase in the cross-section area in the diverging part of the nozzle results in a decrease of the shock wave pressure and an increase in its velocity to supersonic conditions.
- At the nozzle outlet plane, point (2), the motive flow pressure becomes lower than the entrained flow pressure.
- The entrained flow at point (e) enters the ejector, where its velocity increases and its pressure decreases to that of point (3).
- The motive and entrained flow streams may mix within the suction chamber and the converging section of the diffuser or it may flow as two separate streams as it enters the constant cross-section area of the diffuser, where mixing occurs.
- In either case, the mixture goes through a shock inside the constant cross-section area of the diffuser. The shock is associated with an increase in the mixture pressure and reduction

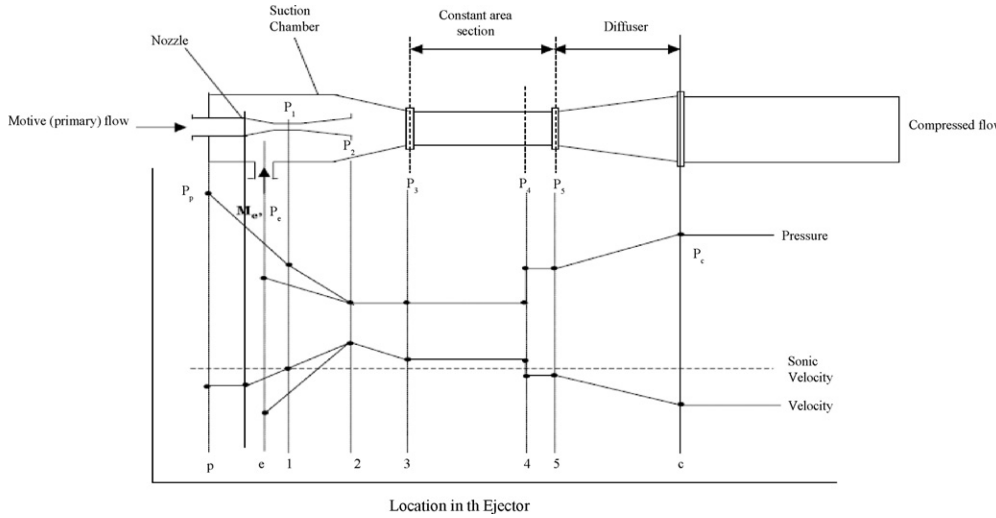

Fig. 3. Variation in stream pressure and velocity as a function of location along the ejector.

of the mixture velocity to subsonic conditions, point (4). The shock occurs because of the back pressure resistance of the condenser.

- As the subsonic mixture emerges from the constant cross-section area of the diffuser, further pressure increase occurs in the diverging section of the diffuser, where part of the kinetic energy of the mixture is converted into pressure. The pressure of the emerging fluid is slightly higher than the condenser pressure, point (c).

Normally, the ejector design can be classified into two types according to the position of the nozzle. The ejector, which has the nozzle with its exit plane located within the suction chamber in front of the constant-area section, as described by Keenan's theory, the static pressure was assumed to be constant through the mixing process. Therefore, this kind of ejector is known as a 'constant-pressure mixing ejector' as shown in Fig. 4a. For the nozzle with its exit located within the constant-area section, the ejector is called a 'constant-area mixing ejector' as shown in Fig. 4b [12–14]. Both types of ejector have been extensively tested experimentally over the intervening years. It was found that the constant-pressure mixing ejector had a better performance than the constant-area one. Therefore, almost all current studies have been focused on the constant-pressure mixing ejector.

4. Working fluids

In this section, the criteria for working fluid selection for the ejector refrigeration systems are provided. The choice of the appropriate working fluid (refrigerant) is one of the most important parts in the design of the ejector refrigeration system. The appropriate refrigerant should yield good performance in the selected operating ranges.

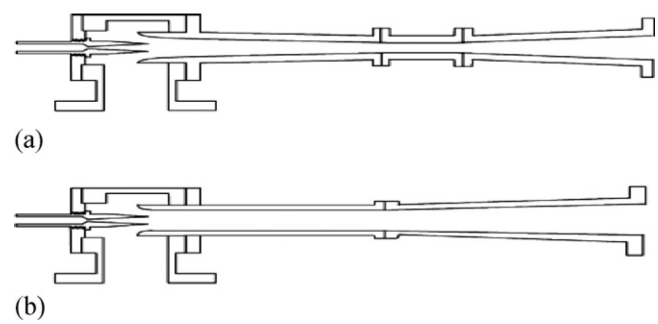

Fig. 4. Schematic view of an ejector: (a) constant-pressure mixing ejector; (b) constant-area mixing ejector.

Table 1 lists some fluids commonly used for experimental studies. The following requirements should be met:

- The fluid should have a large latent heat of vapourization in order to minimize circulation rate per unit of cooling capacity.
- The fluid pressure at the generator temperature should not be too high in order to avoid heavy construction of the pressure vessel and to minimize the power required by pump [15].
- The fluid should be chemically stable, non-toxic, non-explosive, non-corrosive, environmental friendly and low cost [15].
- Transport properties that influence heat transfer, e.g., viscosity and thermal conductivity should be favorable.
- Working fluid with smaller value of molecular mass requires comparatively larger ejectors for the same system capacity. The difficulties of constructing small-scale ejector components should be considered [16]. However, higher molecular mass fluid leads to an increase in entrainment ratio and ejector efficiency [17].

Table 1
Fluids for a jet refrigeration

	R-11	R-12	R-113	R-123	R-141b	R-134a	R-718b (water)
Boling point at 1 atm (°C)	23.7	−29.8	47.6	27.9	32.1	−26.1	100.0
Pressure at 100 °C (kPa)	824	3343	438	787	677	3972	101
Molecular mass (kg/kmol)	137.38	120.92	187.39	152.93	116.9	102.03	18.02
Latent heat at 10 °C (kJ/kg)	186.3	147.6	155.3	176.8	129.4	190.9	2257.0
Global warming potential (GWP)	1	3	1.4	0.02	0.15	0.26	0
Ozone depletion potential (ODP)	1	0.9	0.8	0.016	0	0.02	0
(Wet/dry) vapour	Wet	Wet	Dry	Dry	Dry	Wet	Wet

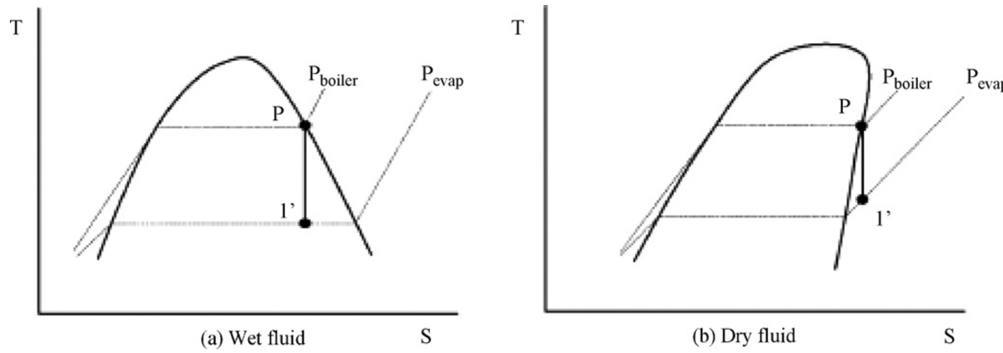

Fig. 5. Expansion process of refrigeration through the primary nozzle.

According to Chen et al. [18], working fluid for a jet refrigerator can be categorized as wet vapour and dry vapour as shown in Fig. 5. For wet vapour fluid, its saturated vapour line forms a negative slope in the *T–S* diagram. For dry vapour fluid, there is no phase change during the expansion process through the primary nozzle. On the other hand, for wet vapour fluid, small droplets may be formed at the nozzle exit, that block the effective are and bump into the wall and cause damage [18,19]. This may be eliminated by superheating the fluid before entering the nozzle. Dry vapour is more desirable than wet vapour fluid. However, the use of superheated motive steam causes a slight decrease in ejector efficiency [19,20].

The most common way of classifying the refrigerant is by the chemical compounds in the refrigerant molecules. They can be classified into four main groups:

(1) Halocarbon group, e.g. R11, R113, R114, R134a, R245ca, R245fa and R152a.
(2) Hydrocarbon group, e.g. methane (R50), ethane (R170), propane (R290), cyclopropane (RC270), butane (R600), isobutane (R600a), and ethyleneglycol.
(3) The compound refrigerants, e.g. R407A, R407B, and R410A.
(4) Other refrigerants, e.g. water (R718) and ammonia (R717).

The following criteria should always be taken into consideration when choosing a working fluid.

4.1. Environmental effect: ozone depletion potential (ODP), global warming potential (GWP)

Several refrigerants yielding high performance are not environmentally friendly. Some have a high ODP (an impact on the stratospheric ozone layer compared to R11) or a high GWP (a factor indicating the relative effect on global warming compared to CO_2). Many working fluids suggested in previous work for ejector refrigeration systems are now, in fact, forbidden due to their environmental effect, such as R11, R113, or R114. New refrigerants are now studied, for example, R123, R134a, R152a and ammonia. R123 is, however, a HCFC working fluid, thus forbidden on many markets. R134a is a relatively strong climate gas and R152a is a weak flammable working fluid with low GWP.

4.2. Safety: toxicity, flammability

Toxicity can be identified by some numbers such as threshold limit value (TLV). Flammability is generally identified by the lower flammability limit (LFL). The ASHRAE standard 34 classifies refrigerants into two classes of toxicity (A = no toxicity identified and B = evidence of toxicity), and three groups of flammability characteristics (1 = no flame propagation in the air at 10 °C and 101 kPa, 2 = LFL more than 0.10 and 3 = LFL less than or equal to 0.10).

4.3. Economics and availability: price and availability

The refrigerant should be cheap and available on the market.

Another advantage of the ejector refrigeration system is the possibility of using a wide range of refrigerants with the system. In experimental and theoretical studies on an ejector refrigeration system, various refrigerants such as steam, ammonia, R11, R123, R113, R114, R141b were selected as working fluid [21–33].

Halocarbon compounds are, or have been, widely used as refrigerants in ejector cycles such as R12, R13, R113, R114, R134a, R141b, R142b or R152a. R113 is a low-pressure refrigerant having high molecular weight; producing a high mass ratio, good ejector efficiency and high compressibility factor which is relatively close to an ideal gas [15]. R141b was used in the solar-ejector cooling system by Huang et al. [25]. For a +8 °C evaporating temperature a COP of around 0.22 is reported at an insolation of 700 W m^{-2}. R142b and R11 are also used in solar applications as described by Dorantès et al. [34], and Chen and Hus [35].

Hydrofluoroether (HFE) was considered for use by Wolpert et al. [36] for a solar-powered ejector air-conditioning system at a cosmetic factory in Mazunte, Mexico. The 13 kW cooling power was designed with an estimated COP of 0.62.

Rusly et al. [14] combined ejector and vapour compression refrigeration systems. Refrigerant R152a was suggested to yield a good performance compared to other refrigerants such as ammonia, R245ca, R245fa and R500. R245fa was chosen by Rusly et al. [14] to be used in the ejector cycle of a combined ejector-vapour compression refrigeration system.

Hydrocarbons are appealing refrigerants for small refrigeration systems. These refrigerants, though natural products, are however, explosive and flammable. They are nevertheless environmentally friendly, with zero ozone depletion potential and low GWP. R600 or N-butane is an interesting refrigerant. Small vapour volume after expansion implies that a large ejector size is not required.

Using water as the working fluid for a jet refrigerator provides many advantages. Its extremely high heat of vapourization causes a low circulation rate for given cooling capacity. Therefore, low mechanical power is required for the pump. Water is inexpensive and has minimal environment impact (zero ozone depletion and global warming potential). However, there are some drawbacks. Using water as a refrigerant limits the cooling temperature to above 0 °C and the system must be under vacuum condition. Moreover, water has very large specific volume at typical evaporator conditions and to minimize the pressure loss, pipe

diameter must be large to accommodate the large volume flow rate [37]. Experiments show that a steam-jet refrigerator requires a boiler temperature between 120 and 160 °C. The system requires relatively low condenser pressure, thus, a water-cooled condenser is a must [38]. Thus, with water as a refrigerant, the useful range of operating temperature is thermodynamically restricted.

Ammonia has been used as a refrigerant for many years, and is still an interesting alternative, yielding good performance in many applications. It is an environmentally friendly fluid (no ODP and GWP) but quite toxic (TLV is 25 ppm). However, it has a strong smell that can be easily detected when released into the environment. The properties of ammonia indicated that it requires more superheating than other refrigerants due to a negative slope of the saturated vapour line, thus condensation may occur inside the ejector causing failure in operation. Higher generating temperatures also require a high superheating temperature.

As previously mentioned, working fluid is an essential part in the ejector refrigeration cycle. Different refrigerants have distinct characteristics and perform differently. Appropriate refrigerants can provide good system performance in selected operating conditions.

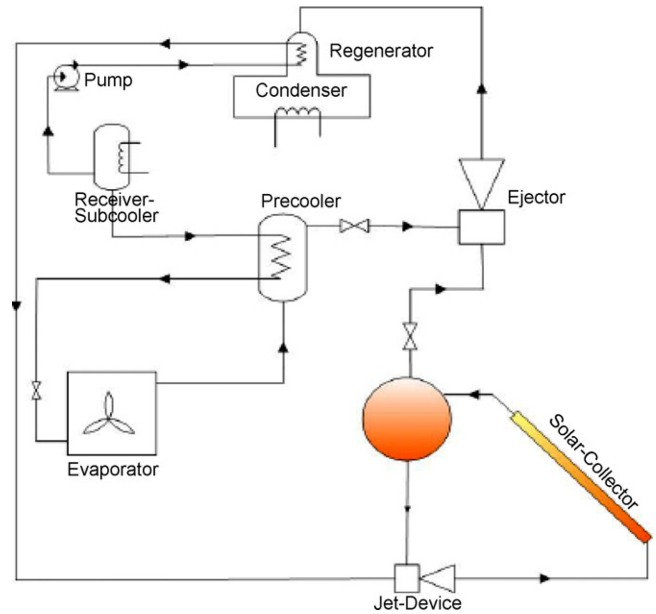

Fig. 6. Single stages solar-driven ejector refrigeration system [25].

5. Various designs of solar-driven ejector refrigeration systems

When any system is designed, the engineers seek to find a solution, which gives maximum efficiency with minimum cost and to reduce the solution time. The optimum system is often not easily found and a lot of calculations and/or simulations are required in order to decide which combination gives the best financial benefit. There are several ongoing attempts to improve the performance of solar-driven ejector refrigeration systems using single, multi-stage ejectors or hybrid system where the ejector technology is combined with other technologies. Many research groups worldwide have performed theoretical calculation, computer simulation and experimental work. More details can be found in the following section.

5.1. Single stage ejector refrigeration systems

A majority of research and development studies regarding solar-driven ejector refrigeration systems deal with the single stage system type. Several experimental rigs have been built and tested in different parts of the world. Initially, CFC refrigerants, e.g. R12 (Chang et al. [39]), R11 (Murthy et al. [40]), R113(Al-Khalidy [41]) were used. After the CFC ban, the HCFCs refrigerants, e.g. R141b (Huang et al. [25]) was used. Subsequently, more environmentally friendly refrigerants were suggested, e.g. the hydrocarbon refrigerant (Pridasawas and Lundqvist [42]) as well as HFE refrigerant (Wolpert et al. [36]).

Al-Khalidy [41] analysed the theoretical and experimental performance of a solar-driven ejector refrigeration system. Five refrigerants (R717, R12, R11, R113 and R114) were compared. From the theoretical analysis, it was found that R113 was more suitable than any other refrigerant. The COP of the refrigeration system and performance of the solar ejector refrigeration system as a whole, increased when the generating and the evaporating temperature increased and decreased when the condensing temperature increases. At a generating temperature of 87 °C, a condenser temperature of 43 °C and an evaporating temperature of 10 °C, the COP obtained was about 0.256 and the STR was 0.12.

Bejan et al. [43] designed a single-stage solar-driven ejector system with 3.5 kW of refrigeration capacity at an evaporating temperature of +4 °C and a generating temperature of 90–105 °C with R114. The overall COP was found to be around 0.126–0.26. The researchers discussed the importance of thermal storage. A cold storage was recommended based on consisting of phase-changing materials, cold water or ice storage instead of storing a large amount of heat on the warm side of the system. Efficiency of the system could be improved by an increase the generating temperature.

Murthy et al. [40] tested different ejector dimensions at the cooling capacity about 0.5 kW. R12 was used as the refrigerant. A COP in the range of 0.08–0.33 was obtained.

Huang et al. [25] developed a solar ejector cooling system using R141b as the refrigerant; obtaining the overall COP of around 0.22

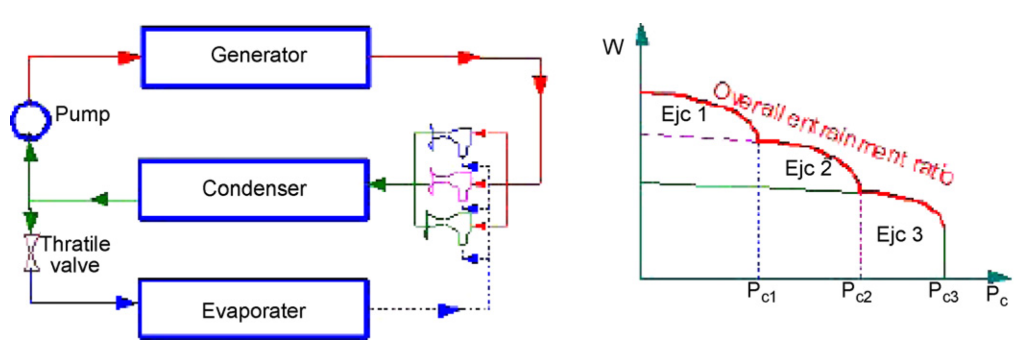

Fig. 7. Multi-stage ejector system.

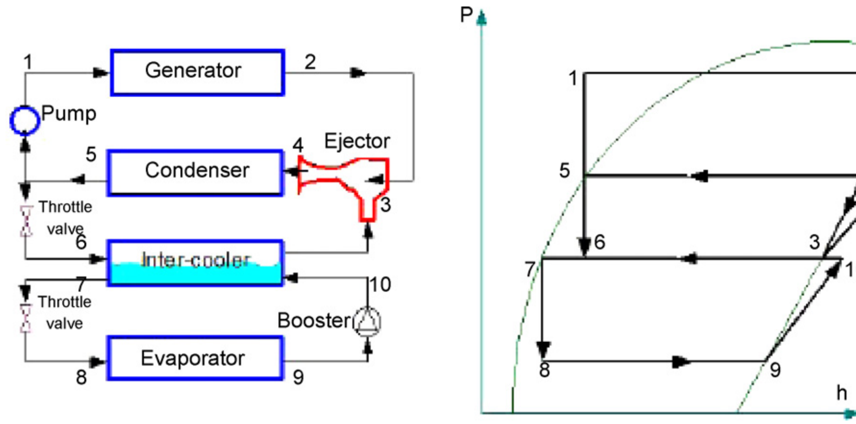

Fig. 8. Ejector refrigeration system with booster.

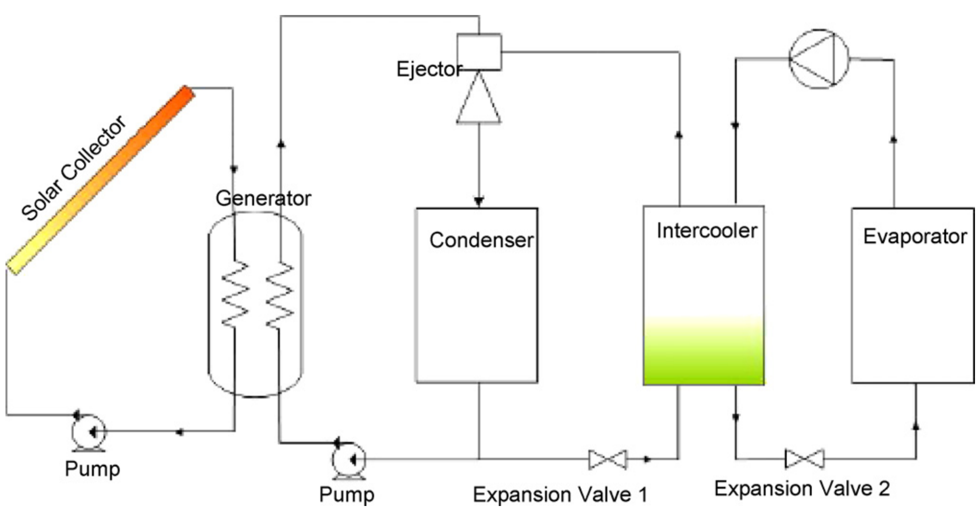

Fig. 9. The solar-power compression-enhanced ejector air conditioner [43].

at a generating temperature of 95 °C, an evaporating temperature of 8 °C and solar radiation of 700 W m^{-2}, see Fig. 6.

Experiments on a solar-powered passive ejector cooling system were also performed in 2001 by Nguyen et al. [33]. Water was used as the working fluid with an evacuated tube solar collector. Cooling capacity was designed for 7 kW. This system is also capable of delivering heat up to 20 kW during the winter period.

Several theoretical analyses and dynamic simulations of the single stage system using butane and iso-butane as refrigerants were performed by Pridasawas and Lundqvist [44–46]. The

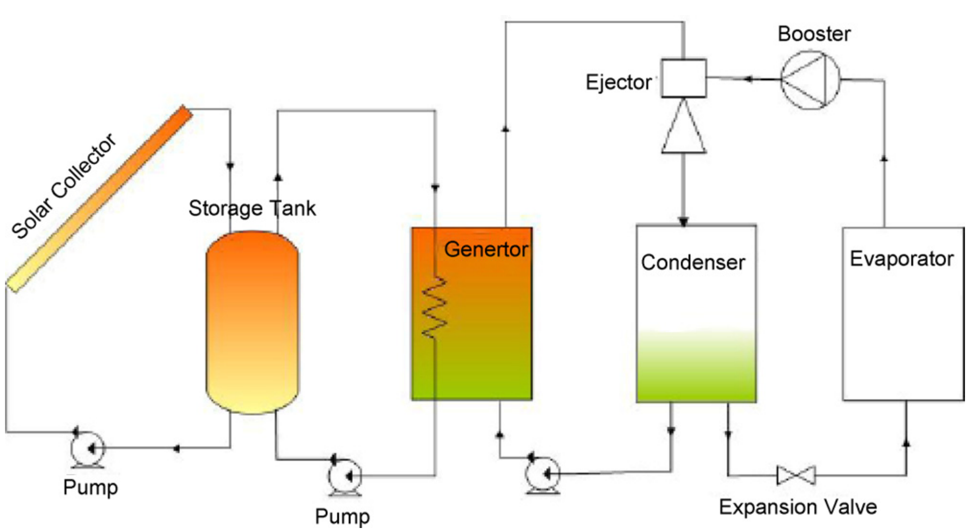

Fig. 10. The solar-driven ejector with booster system [34].

optimum generating temperature was found to be in the range of 80–100 °C, depending on the evaporation temperature. Therefore, high temperature solar collectors are not necessary for the solar-driven ejector refrigeration system being employed for air-conditioning applications.

Wolpert et al. [36] introduced the HFE as a refrigerant for a 13-kW single-stage system. From computer simulations, the COP obtained was about 0.62 at a suggested generating temperature of 140–160 °C, a condensing temperature of 32–40 °C and an evaporator temperature of 5 °C.

R134a was also proposed as a refrigerant for a solar-driven ejector system by Alexis and Karayiannis [47]. The average STR was about 0.014–0.101 and the COP was found to be in the range of 0.05–0.199.

5.2. Multi-stage ejector refrigeration systems

The main technical problem of solar refrigeration is that the system is highly dependent upon environmental factors such as cooling water temperature, air temperature, solar radiation, wind speed and others. One severe restriction for solar cooling in general and the ejector system in particular, is the heat rejection temperature. Heat sink temperatures must be kept as low as possible in order to maintain a stable operation and high performance. A good local heat sink such as a lake, a river or the sea or even a cooling tower can be used with additional parasitic energy consumption for the latter.

Although the single stage ejector refrigeration is simple, it is difficult to keep the system running at optimum conditions due to the variation of working conditions. For example, ambient temperatures above design conditions or low insolation often lead to operation difficulties. Attempts have been made to solve this problem by multi-stage ejectors. Several ejectors are placed in parallel before the condenser. One ejector operates at a time and the operation of each ejector is determined by the condenser pressure. An example of the ejector arrangement is shown in Fig. 7. The overall entrainment ratio is the thick line. Ejector 1 operates when the condenser pressure is above P_{c1}; ejector 2 operates at a condenser pressure between P_{c1} and P_{c2}; and ejector 3 operates at a condenser pressure between P_{c2} and P_{c3}. This arrangement was proposed by Bejan et al. [43].

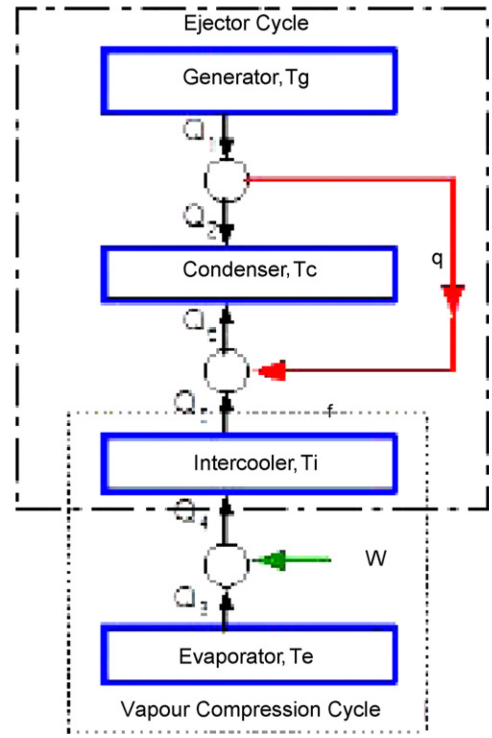

Fig. 12. A concept of a combined ejector refrigeration system [50].

5.3. Ejector refrigeration system with booster or compressor

The low cycle's COP is the main disadvantage of the ejector system; several attempts have therefore been made to improve the performance of this system. A booster (a compressor) can be used to enhance the ejector system at the cost of additional driving energy.

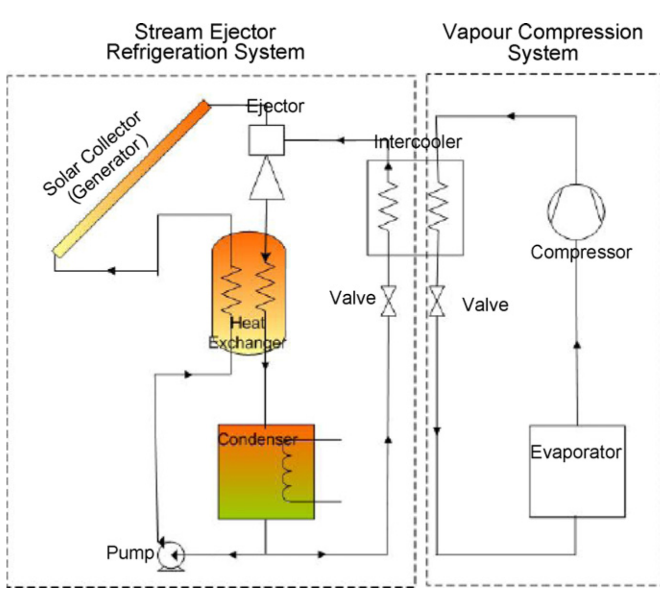

Fig. 11. A combined ejector and vapour compression system [49].

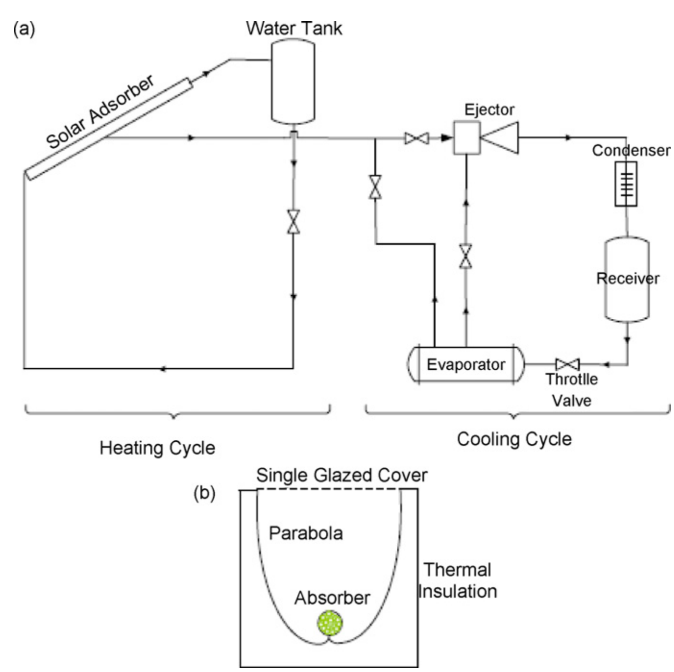

Fig. 13. Solar-driven ejector-adsorption system and an concentrating adsorber [13].

The booster is used to lift pressure of the refrigerant from the evaporator. There are several system configurations proposed by different research groups. An inter-cooler (internal heat exchanger) may be used for maintaining an intermediate pressure. Vapour refrigerant from the evaporator is first boosted to the intermediate pressure. The stream from the intercooler is then supplied to the ejector. A simple diagram of the ejector system with booster is shown in Fig. 8.

Bejan et al. [43] proposed to use a booster and inter-cooler in an effort to improve the ejector cooling system as shown in Fig. 9. Heating, cooling and hot water supply could be the load of the ejector-power system, heating load during the winter and cooling load during the summer. This machine is called 'the solar-powered compression-enhanced ejector air conditioner'. The compression enhanced ejector system is used to boost the pressure of the secondary stream into the ejector. Mechanical energy or electricity is supplied to the booster. R114 is used as the working medium. Whole system performance can be improved. At 3.5 kW of the refrigeration capacity, 4 °C evaporating temperature and 50 °C condensing temperature, the theoretical COP of the ejector system can be up to 0.85 and the COP of the overall cycle can be up to 0.5. In 2004, this research group revised the system again with an HCFC refrigerant, Arbel and Sokolov [48]. The previous CFC refrigerant (R114) was replaced by R142b.

An ejector system with a booster using R142b was proposed by Dorantès et al. [34] is shown in Fig. 10. There was no inter-cooler in the system. Dynamic simulations of the solar-driven system demonstrated that the COP achieved was about 0.11 at an evaporating temperature of −10 °C, condensing temperature of 30 °C and generating temperature of 105 °C. This system could produce 100 kg of ice per day at the capacity of 2 kW.

The system with two split methods: vapour compression and ejector system was proposed by Sun et al. [49] is shown in Fig. 11. Water was used as the refrigerant in the ejector system, and R134a was used in the vapour compression system. The condenser of the vapour compression system performed as the evaporator of the ejector system. This equipment is defined as an intercooler. Results

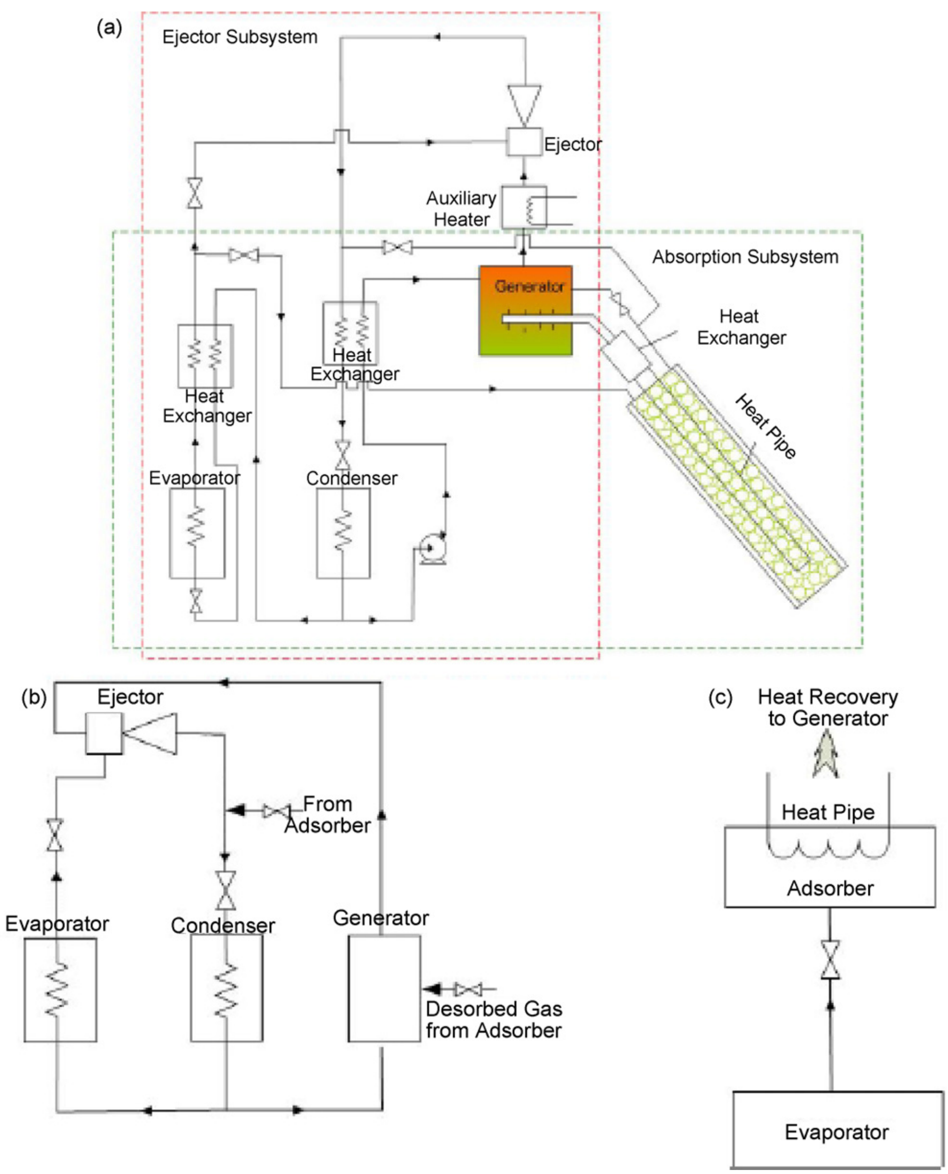

Fig. 14. Solar-driven ejector-adsorption system proposed [51]. (a) System layout; (b) ejector refrigeration system during day time; (c) adsorption refrigeration system during time.

from the theoretical analysis illustrated that this combined cycle can improve system efficiency by more than 50%.

A solar-assisted ejector-vapour compression cascade system was proposed by Göktun [50]. The inter-cooler was installed serving as a condenser for the vapour compression system and an evaporator for the ejector system as shown in Fig. 12. This paper also proposed an equation for calculating the optimum operating solar collector temperature and corresponding COP.

5.4. Solar-driven combined ejector and adsorption refrigeration systems

This system can be considered as two split cycles which work separately at different periods: an ejector cycle and an adsorption cycle. The system was proposed by Zhang and Wang [13] and Li and Wang [51]. The theoretical analysis of a solar-driven continuous combined solar adsorption-ejector refrigeration and heating system was presented by Zhang and Wang [13]. A schematic of this system is shown in Fig. 13. Zeolite–water was used as a working pair. This system is working on the same principle as the system proposed by Li and Wang [51]. The difference is in the afternoon, when the temperature in the adsorber is high enough; the adsorber is used as a thermal collector for heating up tap water. The cooling capacity is 0.15 MJ/kg Zeolite during day time and 0.34 MJ/kg Zeolite in the evening. This system can also heat up 290 kg of water to 45 °C. A combined COP of about 0.33 was reached.

The proposed system by Li and Wang [51] is shown in Fig. 14. Zeolite 13X and water are used as the working media. During day time, the cooling effect is achieved by the ejector cycle; while the desorption process occurs in the adsorption cycle. The vapour from the desorption process of the adsorber enters the generator. During night time, the cooling effect is achieved by adsorption process; vapour refrigerant from the evaporator is adsorbed in the adsorber. The overall COP of this combined cycle is about 0.4, at the regeneration temperature 120 °C, a desorption temperature of 200 °C, a condensing temperature of 40 °C and an evaporating temperature of 10 °C.

5.5. Solar-driven combined ejector and absorption refrigeration systems

A conventional absorption refrigeration system consists of two pressure levels, a high-pressure side in the condenser and the generator, and a low pressure side in the evaporator and the absorber. An expansion valve and pressure-reducing valve are the common equipment used to split the high and low-pressure sides. Both valves operate on a throttle process causing inefficiency in the system. Thus, the idea of a combined cycle is to reduce throttle loss by using an ejector. The ejector is introduced in order to utilise energy from the high-pressure side of the weak solution in the generator. The high-pressure weak solution in the generator expands through the nozzle in the ejector and creates a vacuum at the other end of the ejector. As a vacuum occurs, the vapour from the evaporator is drawn into the ejector.

Sözen and Özalp [52] proposed a solar-driven ejector-absorption system operated with aqua-ammonia. The proposed schematic is shown in Fig. 15. The main focus of this study is to investigate the possibility of using this system in Turkey. As a result of the analysis, using the ejector, the COP improved by about 20%. According to results obtained in this study, for 8–9 months (March–October) of the year, the collector surface area of 4 m^2 is sufficient for different applications of refrigeration all over Turkey.

Theoretical and experimental study of solar-ejector absorption refrigeration system was conducted by Abdulateef et al. [53]. A schematic system is shown in Fig. 16. The first purpose of the study is to design and construct an ejector refrigeration system powered

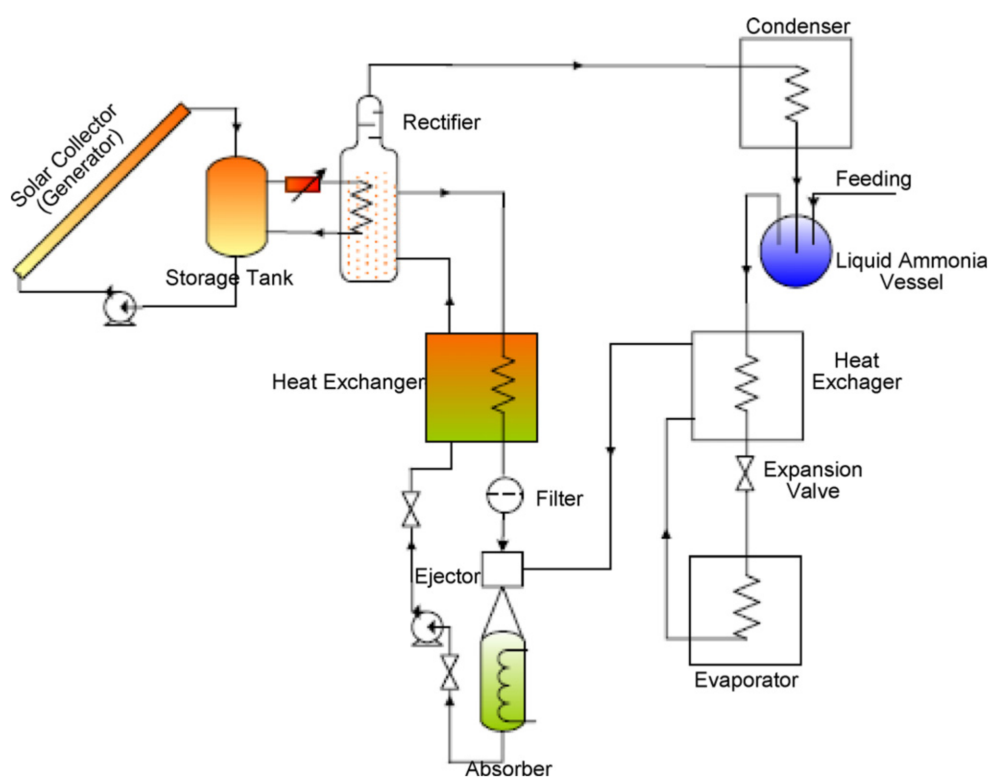

Fig. 15. Schematic of a combined ejector-absorption refrigeration system powered by solar energy [52].

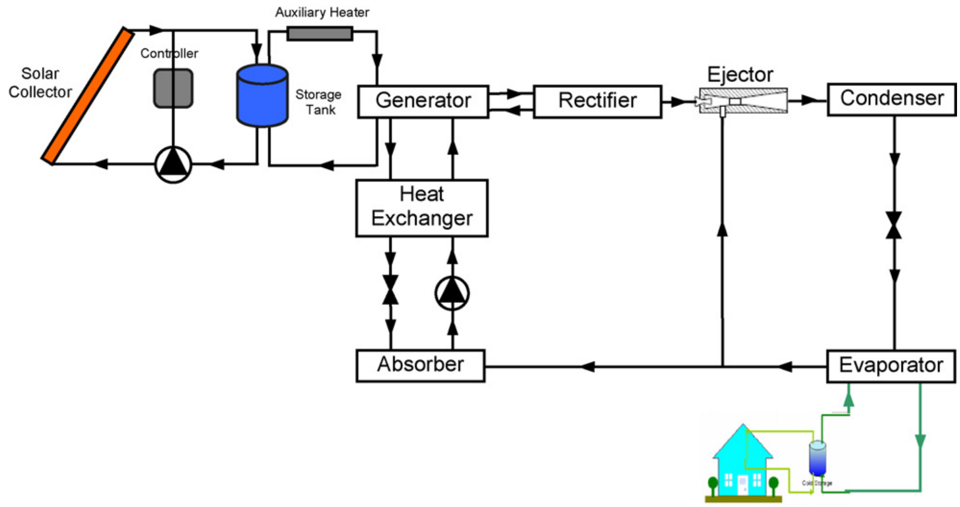

Fig. 16. Solar-driven ejector absorption refrigeration system [53].

by solar energy and NH_3–H_2O as working fluid. The second purpose of the study is to investigate the effects of the operating conditions on the COP and the cooling capacity of the system. A mathematical model is developed for design and performance evaluation of the ejector refrigeration system. The mathematical model cover a wide range of compression, expansion and entrainment ratios, especially those used in industrial applications.

The widely used refrigeration system is based on the aqua-ammonia absorption cycle. It is suitable for solar energy applications. The aqua-ammonia combination has acceptable thermo physical properties for the ejector absorption refrigeration system.

6. Conclusions

This paper describes a basic background and development on solar-driven ejector refrigeration technologies. One may conclude that solar-powered ejector refrigeration technologies could be used for producing a wide range of temperatures of cold. They are attractive technologies that not only can serve the needs for refrigeration, air-conditioning applications and ice making, but also can meet demand for energy conservation and environment protection. Comparatively, absorption systems are more suitable for air-conditioning while adsorption systems are more employed for low temperature purpose. A variety of options is available to convert solar energy into refrigeration effect. Solar thermal with single-effect absorption system appears to be the best option closely followed by the solar thermal with single-effect adsorption system. Solar photovoltaic options are significantly more expensive.

Various kinds of working fluids can be used in the cycle; each of these providing different performance and characteristics. Choosing a working fluid concerns several issues, particularly physical and thermodynamic characteristics. Apart from general issues such as chemical stability, environmental impact or toxicity, the curve of the saturated vapour line in a temperature–entropy diagram (T–S) should be taken into consideration. Dry fluids, e.g. butane, iso-butane, R113, R114, and R141b require less excessive energy for superheating, therefore, they yield better performance than wet fluids and isentropic fluids at the same operating temperatures.

In steady-state analysis of the ejector refrigeration system it has been shown that system performance depends on the type of refrigerant, the operating conditions and the ejector geometry. In practice, the cooling load and the climate are dynamic. The main technical problem of solar refrigeration is that the system is highly dependent upon environmental factors such as cooling water temperature, air temperature, solar radiation, wind speed and others. Thus, dynamic simulations are required for the dimensioning of the equipments in the system, rather than steady state analysis. Furthermore, the designer can better understand the influence of the local conditions on the function of the system. Due to the low efficiency of the ejector cycle, it is not economically competitive to operate the system with low solar fraction.

However, a lot of research work still needs to be done to improve performances of solar-driven ejector refrigeration systems. It is hoped that this contribution will stimulate wider interest in the technology of ejectors and their applications in refrigeration system. It should be useful for any newcomer in this field of technology.

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